Drifter Motion Planning for Optimal Surveillance of the Ocean (DRIMPOS)

A C. Poje
Department of Mathematics - Graduate Physics Faculty
College of Staten Island, City University of New York
Staten Island, NY 10314
phone: (718) 982-3611 fax: (718) 982-3631 email: poje@math.csi.cuny.edu

Award Number: N000140710588

LONG-TERM GOALS

In recent years substantial progress, much of it resulting directly from ONR funding initiatives, has been made in understanding fundamental features of transport and mixing in oceans using methods derived from dynamical systems theory. The purpose of the current collaborative research is to extend these methods to the design of control algorithms for Drifter Motion Planning for Optimal Surveillance of the Ocean (DRIMPOS). This effort is a direct attempt to transition Lagrangian based dynamical systems methods from diagnostic, postdictive tools to essential and active components in the design of oceanographic and naval observing systems. The specific goals of the research project include the development of flow-based control algorithms for drifting autonomous sensing systems.

OBJECTIVES

Couple dynamical systems ideas and control-theoretic algorithms to produce real-time control of gliders based on the output from high resolution coastal ocean model forecasting systems. Specifically, use knowledge of Lagrangian ocean dynamics to develop readily computable, optimal control algorithms to (1) maximize the loitering time of autonomous surveillance platforms in a prescribed region under energy constraints (2) minimize the distance, over an extended time period, between a platform and a specified location in the flow (3) optimize sensor coverage of a given surveillance region by single or multiple platforms and (4) perform optimal path planning for an AUV platform by minimizing time to reach any number of specified way-points along a desired observational route.

APPROACH

Work completed under this grant involves close collaboration with Igor Mezic at the University of California Santa Barbara. Non-linear optimal control theoretic ideas formulated by the UCSB group have been adapted for implementation in the highly inhomogeneous, time-dependent flow fields produced by high-resolution ocean prediction models. For illustrative purposes we consider 1km resolution, data-assimilating hind-casts of the Adriatic Sea from the Naval Coastal Ocean Model (NCOM) provided by Paul Martin at NRL-Stennis. An extremal field algorithm, originally proposed in the context of time-independent input velocity fields, is extended to non-autonomous inputs to solve Zermelo's minimum time navigation problem efficiently. The result, for a given input ocean velocity field, is the optimal feedback controller for an idealized autonomous vehicle along with the associated optimal cost function.

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **2010**	2. REPORT TYPE	3. DATES COVERED **00-00-2010 to 00-00-2010**

4. TITLE AND SUBTITLE **Drifter Motion Planning for Optimal Surveillance of the Ocean (DRIMPOS)**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **City University of New York,College of Staten Island,Department of Mathematics,Staten Island,NY,10314**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Our approach is to cast the optimal AUV control problem in the context of minimum time Hamilton-Jacobi-Bellman equations for which the value function (and the thus the optimal feedback controller) is (a) discontinuous and (b) dynamic. In particular, we develop a robust solution algorithm which is readily applicable to the gridded, time-varying flow fields produced by realistic operational ocean prediction models. The solution algorithm is Lagrangian in nature relying on accurately solving Euler-Lagrange equations for the states and co-states of a large number of initial conditions and then efficiently filtering for optimality. The procedure allows for incremental refinement of the solution and is inherently suited to large-scale computational parallelism.

The algorithm consists of two parts. First the Euler-Lagrange equations are integrated backward from some desired final state(s) and/or moving target(s) over a dense sampling of the (unknown) possible final costates. This generates a field of extremals in the 3-D space given by the 2 space dimensions and time. The 3-D field is then filtered to remove possible suboptimal extremal points leaving, at any initial time, a gridded field of optimal trajectories and their associated costs. Optimal feedback control can then be determined from the gridded cost-function. The algorithm can be adapted to handle general cost functions–e.g. combinations of time and energy, general bounded or unbounded velocity vector inputs, and general glider/ship models.

WORK COMPLETED

1) A refereed manuscript detailing and verifying both the accuracy and efficiency of the control algorithm has been accepted for publication in the proceeding of the 49th IEEE Conference on Decision and Control. [1]
2) A manuscript detailing the application of the control algorithm to AUV/glider control in realistic ocean models is nearing completion for submission to IEEE journal of Ocean Engineering. [2]
3) Preliminary analysis of 3D model data has begun. Using realistic glider dive protocols obtained from NRL Stennis and available model data for the South China Sea region, we have begun assessment of the role of vertical shear on horizontal control of autonomous vehicles.

RESULTS

Results detailing the application and efficiency of the control algorithm for maneuvering autonomous sensor platforms for maximum loitering time in extended (*O*(20 x 20 km)) regions were considered previously. We showed, in the context of a well documented NRL coastal model of the Adriatic Sea, that the optimal control algorithm can provide an order of magnitude increase in the residence time of a glider in such a region when compared to simple, a-priori path planning strategies. In the current year of funding we have focused on additional path planning applications, namely station keeping in the presence of strong currents and minimum time way-point tracking. In each, we examine the role of time-dependence in supplied model current field and the relationship between the derived optimal trajectories and Lagrangian Coherent Structure boundaries in the model data.

Role of Time Dependence : Figure 1 shows a comparison of two control strategies, (1) optimal control as obtained by forward in time solution of the HJB equations using the proposed algorithm and (2) constant radial control towards the target point. The results are obtained using NCOM model output (*Martin et al* [3]) for the Adriatic Sea from 2006. The geographic region is the eastern Italian Coast in the strong Western Adriatic Current (WAC). The control problem is to direct a glider, with control

velocity < 20% of the maximum current speed, from an initial position west of the WAC ((60,710) in grid units) to final position (90,690) east of the jet. To assess the importance of time dependence for controllability, we consider both the raw model current fields available hourly (shown in lower panels) and the time independent, monthly mean current field (shown on the upper panels). As shown in the figures, the time-dependent control algorithm makes explicit use of temporal fluctuations (dominated by tidal signals) in the current field to effect control. While simple radial control is incapable of directing the slow glider to the target location in either the mean or time dependent cases, comparison of the upper and lower right-hand panels shows that control algorithm produces the desired trajectory.

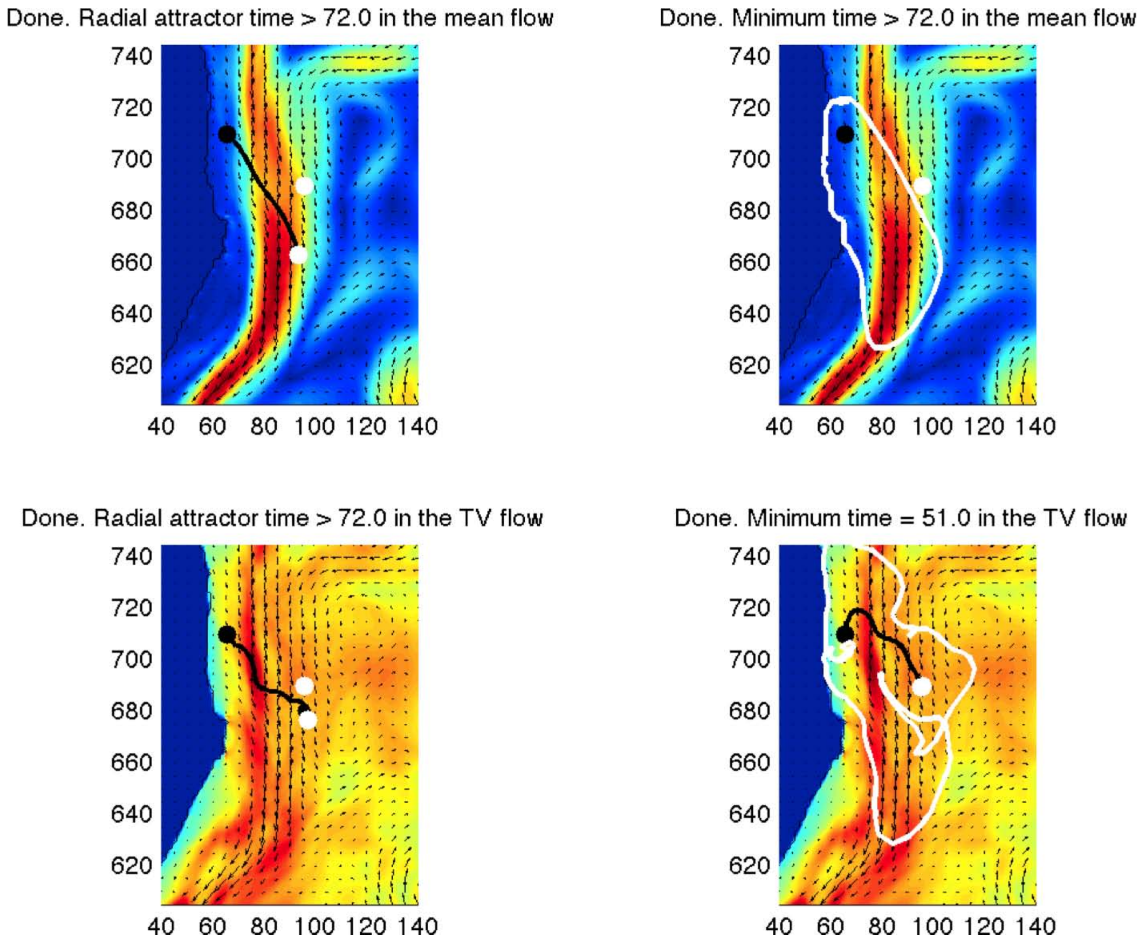

Figure 1: Comparison of optimal control (left panels) and simple radial control (right panels) in both time independent mean flow (upper panels) and fully time dependent model flow (lower panels). The geographic region is the strong WAC north of Gargano in the NCOM Adriatic simulation. Initial AUV position is shown by black circle and target position by white circle at approximately (90,690). In optimal control cases, extent of reachability front is given by closed white curve. Note the increased extent of reachability front in time dependent flow. Optimal trajectory uses local-in-time decrease in jet speed to initially move north in order to reach target in 51 hours.

Station-Keeping in strong current fields: Given the importance of time dependence for controllability, we examine the ability of the control algorithm to provide station keeping for AUVs even in regions where the nominal mean current amplitude exceeds the operational speed of the sensor platform. Figure 2 again shows a comparison of simple radial control to optimal for such a situation. In this case the flow area is in the eddying region of the central Adriatic between the northern and southern gyres. The control task here is to maintain the AUV in the 1km x 1km open circle on the southwestern edge of an anti-cyclonic eddy (centered ~ at (150,605)). The mission length is 10 days. As seen in the time series of headings, the crucial aspect of the optimal control occurs on day 3 (t ~ 80 hours) when the AUV is controlled to the east, temporarily farther from the target, to allow superior station keeping for the duration of the mission. Subsequent analysis (not shown) indicates that this motion is across a finite-time transport barrier associated with the hyperbolic region produced by the eddy. The 'distance-to-target' time series clearly indicates that the solution to the optimal control problem provides a trajectory with much smaller average and maximum distance from target.

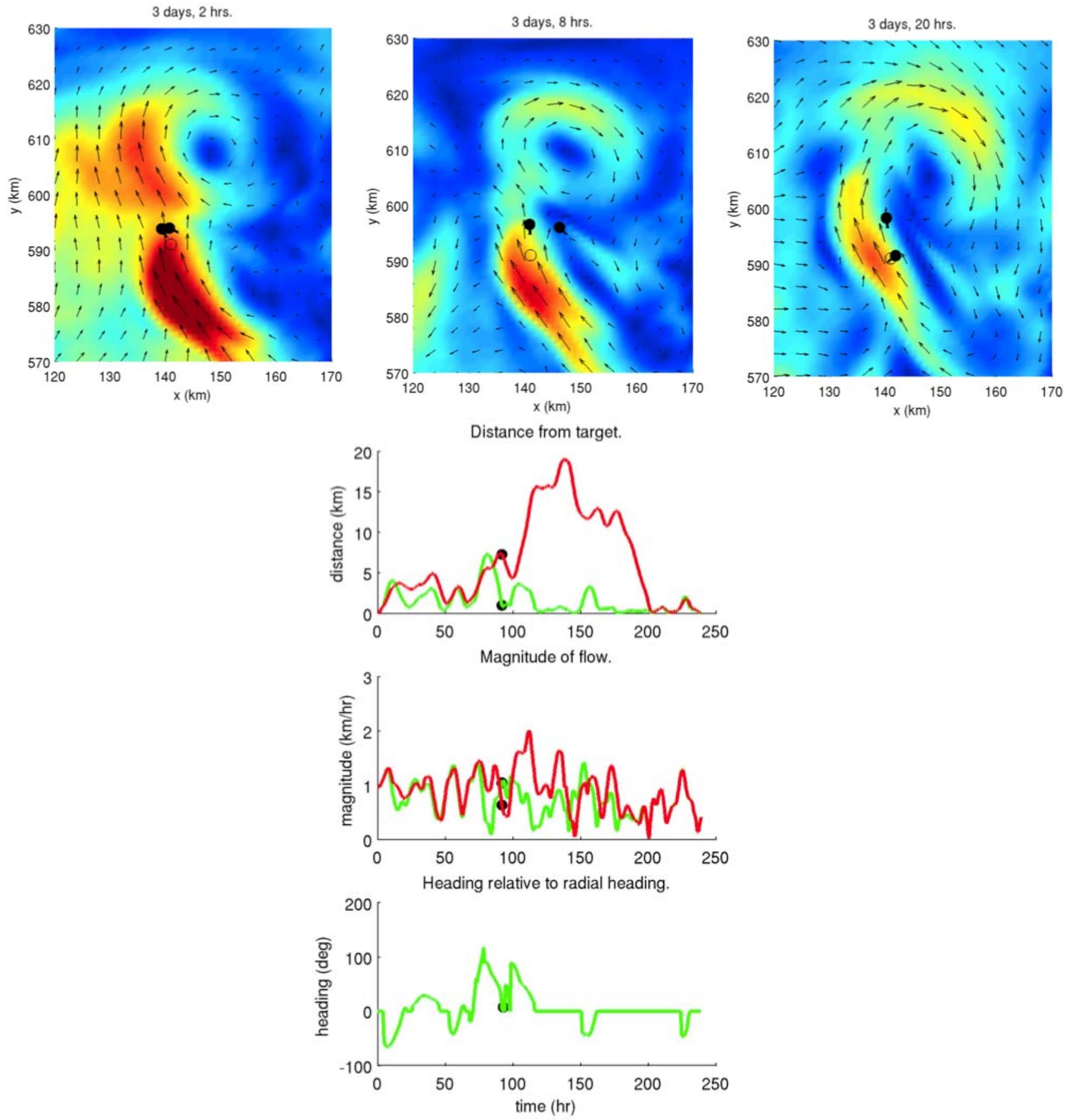

Figure 2: Top row: Snapshots of the position of the AUV under both simple radial control and optimal control at three different times. The open circle indicated the desired station keeping location. Bottom: Graphs of the distance to the desired target, local flow speed, and heading relative to radial heading versus time for the ten-day mission. Note the critical decision making at time 3 days, 8 hours where the optimal controller acts to move further from station (black circle at ~(148,597) so that it may better perform station keeping at subsequent times.

Optimal Waypoint Tracking: As a final demonstration of the utility of the optimal control algorithm we consider the problem of steering, in the presence of strong time-dependent currents, a glider through a specified set of way points. As an example, we specify four measurement stations in the complicated re-circulating flow south of the Gargano Pennisula as shown in Figure 3. The control task is to steer an idealized AUV clockwise through the four points while minimizing the time of travel from waypoint to waypoint. As expected from the snapshot of the velocity field, the ambient currents do not permit one to simply steer towards the next waypoint - successful completion of the observation circuit requires taking explicit advantage of the time dependence of the flow field.

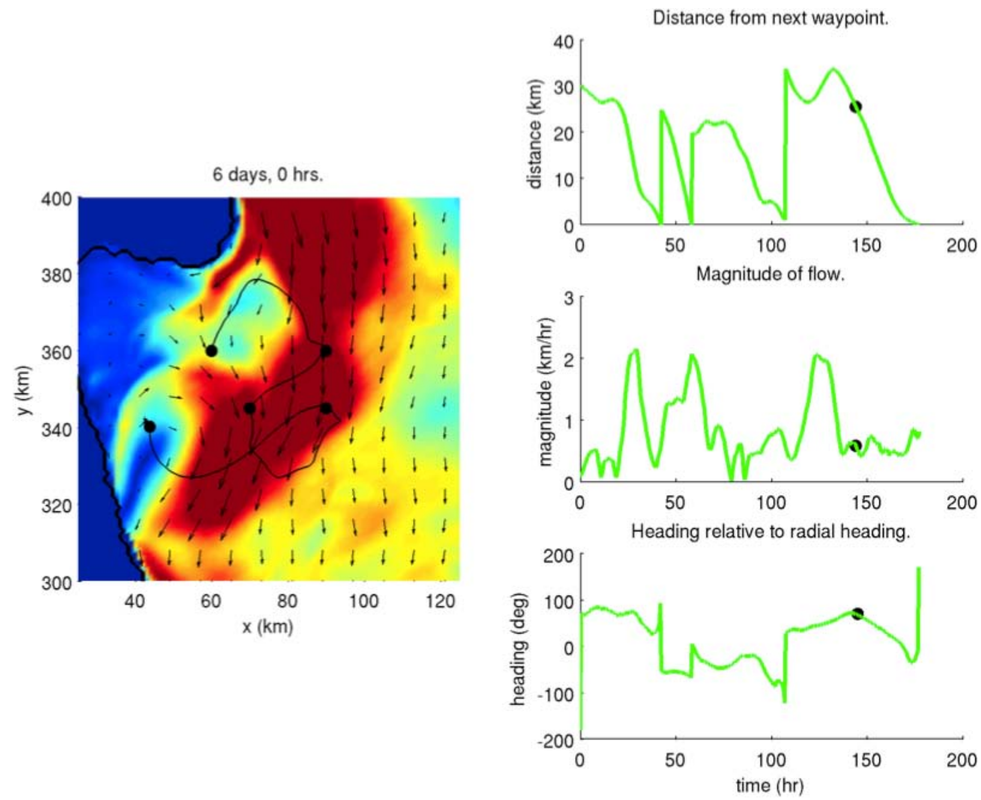

Figure 3: Example of optimal control algorithm applied to minimize time to next waystation. Geographic region is separated and eddying WAC south of Gargano Pennisula. The prescribed mission is to direct AUV through 4 points indicated by black circles at (60,360), (90,360), (90,340), (70,340) successively. Controlled trajectory is shown in black, AUV position at t = 6 days, near final leg of mission is also shown. Right panel indicates distance to next way point, local flow magnitude and heading relative to radial heading versus time. Note the need to travel west in order to find favorable flow conditions for the final, northerly portion of cycle.

IMPACT/APPLICATIONS

The research conducted during the final year of funding serves extends the application of rigorous and objective optimal control theory to a number of practical AUV/glider operational strategies. The algorithms developed are explicitly suited to computing optimal control in the context of highly nonlinear, time-dependent numerical vector fields derived from ocean model output. Modest funds available for the continuation of this project will be used to investigate the effects of vertical shear in the model horizontal velocity fields.

RELATED PROJECTS

This work is collaboration under the ONR PLUS effort with Prof. I. Mezic´ and his group at the University of California Santa Barbara. The PI actively collaborates with Professors T. Ozgokmen and A. Griffa at the University of Miami on ONR funded research concerning Lagrangian data

assimilation, optimal deployment strategies, model-data intercomparison and the sensitivity of Lagrangian Coherent Structure boundaries to model error and filtering. Similarly, the PI continues regular collaboration with Professors A.D. Kirwan and B. Lipphardt at the University of Delaware. All named collaborators are active participants in the ONR MURI proposal ' DYNAMICAL SYSTEMS THEORY IN 4D GEOPHYSICAL FLUID DYNAMICS' recently slated for funding.

PUBLICATIONS

1) B. Rhoads, I. Mezic' & A.C. Poje, *Minimum Time Control of Autonomous Underwater Vehicles*, Proceedings of the 49th IEEE Conference on Decision and Control, 2010 (refereed, in press).
2) B. Rhoads, I. Mezic' & A.C. Poje, *Optimal Control of Autonomous Underwater Vehicles in Time Dependent Flows*, IEEE Journal of Ocean Engineering, 2010 (to be submitted).
3) A.C. Haza, A. Griffa, P. Martin, A. Molcard, T.M. Ozgokmen, A.C. Poje, R. Barbanti, J.W. Book, P.M. Poulain, M. Rixen, P. Zanasca, Model-based directed drifter launches in the Adriatic Sea: Results from the DART experiment. *Geophysical Research Letters*, **34**, L10605, (2007).